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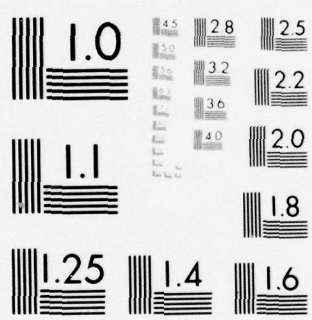

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DECEMBER 1976

PROJECT MANAGEMENT THROUGH SIMULATION

A.M. FEILER

UCLA • SCHOOL OF ENGINEERING AND APPLIED SCIENCE

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The role of critical path network analysis in project management is discussed. Specific shortcomings of conventional, deterministic network analysis techniques are outlined and examples are given of the individual factors which contribute to the overall optimism of deterministic analysis. Computer simulation is offered as a means of developing realistic schedules, budgets and resource requirements for projects where uncertainty and performance variability are of significance.

PROJECT MANAGEMENT THROUGH SIMULATION

Prepared for

The Department of the Navy

Under Contract N00014-76-C-0112

School of Engineering and Applied Science
PROJECT TRANSIM
Los Angeles, California 90024
December 1976

Letter on file

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PROJECT MANAGEMENT THROUGH SIMULATION

INTRODUCTION

In recent years, as acquisition projects have become larger and more complex in scope, there have been an increasing number of near-catastrophic project overruns receiving national attention as well as countless of other projects of lesser scope and public visibility which have suffered the same fate. The overrun pattern has become so much a part of the general project scene that it has almost become axiomatic that planned project schedule and budget targets will prove to be optimistic. The only question remaining is: "By how much?"

As a consequence, there has been an increasing amount of research in both government and private sectors on the causes of project overruns, much of it centering on the problems of the project management process itself.

Project management of a large acquisition project is a difficult job demanding the most effective of management methods. The project manager is responsible for getting the job done on schedule and within budgeted cost. In most cases, he must accomplish his goals by integrating the efforts of a number of different organizations and individuals, many of whom are not under his direct control. Such a diverse group may include analysts, designers, contract administrators, laboratory technicians, construction workers, purchasing agents, and vendors and suppliers. The project manager must also negotiate, communicate, coordinate, and interface

his activity with other projects, different government agencies, and various management levels in his own agency.

The many difficulties associated with effectively managing and coordinating the efforts of such diverse groupings have been somewhat alleviated in recent years by the availability of computerized, critical path network-based project management systems which provide assistance in planning, budgeting, scheduling, and controlling complex projects.

In the fifteen years since the PERT and CPM techniques were first introduced, critical path network applications have extended to virtually every type of project in government and industry. With the continuing increase in interest, there has been a proliferation in the number and capabilities of different network analysis software packages which are available to assist the project manager.

Yet, the availability of such sophisticated project management tools has not generally provided the hoped-for major improvement in project performance. Certainly, the overall project environment in which such techniques are used is most important to their successful application. It would be difficult for a critical path technique to work effectively unless there is adequate top management support, effective project organization, proper designation of authority and responsibility, efficient communication and information flow, and the other desirable features of any well-designed project management environment.

Is the critical path technique all that has been claimed even in a favorable management environment? Or is it merely a computerized placebo lulling project management into expecting that project problems will be taken care of. Consider, for instance, all the different kinds of output reports containing all the project statistics a manager could want.

It is my belief that the critical path technique may not only be ineffective, but may also be a major contributing factor to project overruns. Its accuracy deficiencies, when applied to certain kinds of projects, have been recognized for some time. Investigations[1] have demonstrated that for many projects the conventional critical path technique produces misleading results because of its inability to deal with impacts of project uncertainty and project activity variability where they are significant factors. Such projects typically include R and D, weapon system acquisition, public works, large construction projects, urban redevelopment, and similar complex projects.

The investigations have shown that where uncertainty and variability are not accounted for, project schedule and budget targets tend to be optimistic; the degree of optimism for individual projects varying from 10 to 50 percent or more. Project overruns thus become inevitable when optimism is built into the project plan, schedules, and budgets by the network analysis technique, itself.

FACTORS CONTRIBUTING TO UNCERTAINTY

All project managers face some degree of uncertainty. However, few encounter the type and magnitude of uncertainty facing the project manager of a large and complex acquisition project. A few examples are:

- -- uncertainty regarding pertinent actions by government agencies
- -- uncertain rate of technological development, or probability of successful attainment of technical targets
- -- uncertainty regarding the nature of the work to be performed, as described by the project plan.

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1 See References 1, 2, and 3

-- errors and omissions in working drawings
-- delays in obtaining top management approvals
-- effects of weather on fabrication work
-- uncertain delivery dates for purchased material and equipment
-- uncertain results of system test and checkout
-- uncertain rate of cost escalation
-- normally variable work performance rates
-- mechanical breakdown or malfunction
-- rejection of poor quality work

PROJECT RISK

Where there's uncertainty - there's risk. Project management is usually well aware of the high likelihood that its targets - schedules, budgets, and technical objectives - may not be met. The words "uncertainty" and "risk" have become part of the project manager's normal jargon because they reflect the uneasiness and apprehension he often faces when he is required to make project decisions. Despite the use of computerized techniques, "using the crystal ball," "guesstimating," "tossing a coin," and "adding contingency allowance" still remain in frequent management use when coping with project decisionmaking under uncertainty.

Despite the recognized importance of uncertainty to project performance, the analytical means of determining the resulting risks and assisting the project manager in dealing with uncertainty and risk have received little attention in practice. We can only speculate as to the number of past project overruns which could have been avoided if project management had available an effective technique for accounting for uncertainty and controlling projects within acceptable risk levels.

SHORTCOMINGS OF CRITICAL PATH TECHNIQUES

Although experienced project managers recognize many of the project uncertainties they face, their ability to cope with uncertainty-related

problems is limited because of the shortcomings of analytical techniques. The basic problem is that conventional critical-path techniques such as PERT, CPM, and other similar techniques which are now receiving widespread use for planning, scheduling, resource analysis, and costing -- are all "deterministic." That is, they depend upon single-value data inputs to the network plan and analysis and therefore, cannot account for the many uncertainties which are inherent to real-life project performance. The inability to account for uncertainty makes it difficult to identify and deal with the complex interactions that can develop among the project activities.[1] Unfortunately, such interactions can profoundly affect overall project performance. They invariably add to project duration and increase its cost and they rarely improve project performance.

The magnitude of the optimistic bias of deterministic network analysis results is determined by a number of factors:

1. The particular project activity network configuration
   a. the length (time-duration) of the longest time path relative to the other paths
   b. the number of near-critical paths, i.e. very close in time duration to the critical path
   c. the number of common nodes among the paths which have some level of criticality
   d. the number of activities which have less than 100 percent probability of occurring
2. The degree of variability of task performance of activities on the critical path and on near-critical paths.
3. Allocation of scarce resources based on deterministically-determined resource requirements.

One of the more misleading aspects of conventional deterministic methods is the assumption that there is a unique "critical" path (longest time path) in a project network. Where individual project activity perfor-

mances are variable, there are usually several paths which could prove to be longest, depending upon the eventual realization of activity times. The probability that an individual activity will lie on the longest time path for a specific network realization is a measure of the activity's "criticality."[2] Accordingly, the activities requiring close managerial attention are those with significant criticality - and should not be limited to those on the single critical path of deterministic techniques. In a typical project, as many as 50 to 60 percent of the project activities can have a significant level of criticality.

EXAMPLE PROJECT NETWORK

The factors contributing to the optimistic bias of conventional deterministic network analysis techniques are demonstrated for the case of a Navy ship boiler repair project network in Figure 1. The boiler project consists of 28 activities, all exhibiting variability in time performance (See Table I).[3] As examples of the variability of the time to execute a project activity task, Figure 2 shows the time distributions obtained from field observations for Activity 08 - Remove Refractory Material, Activity 13 -

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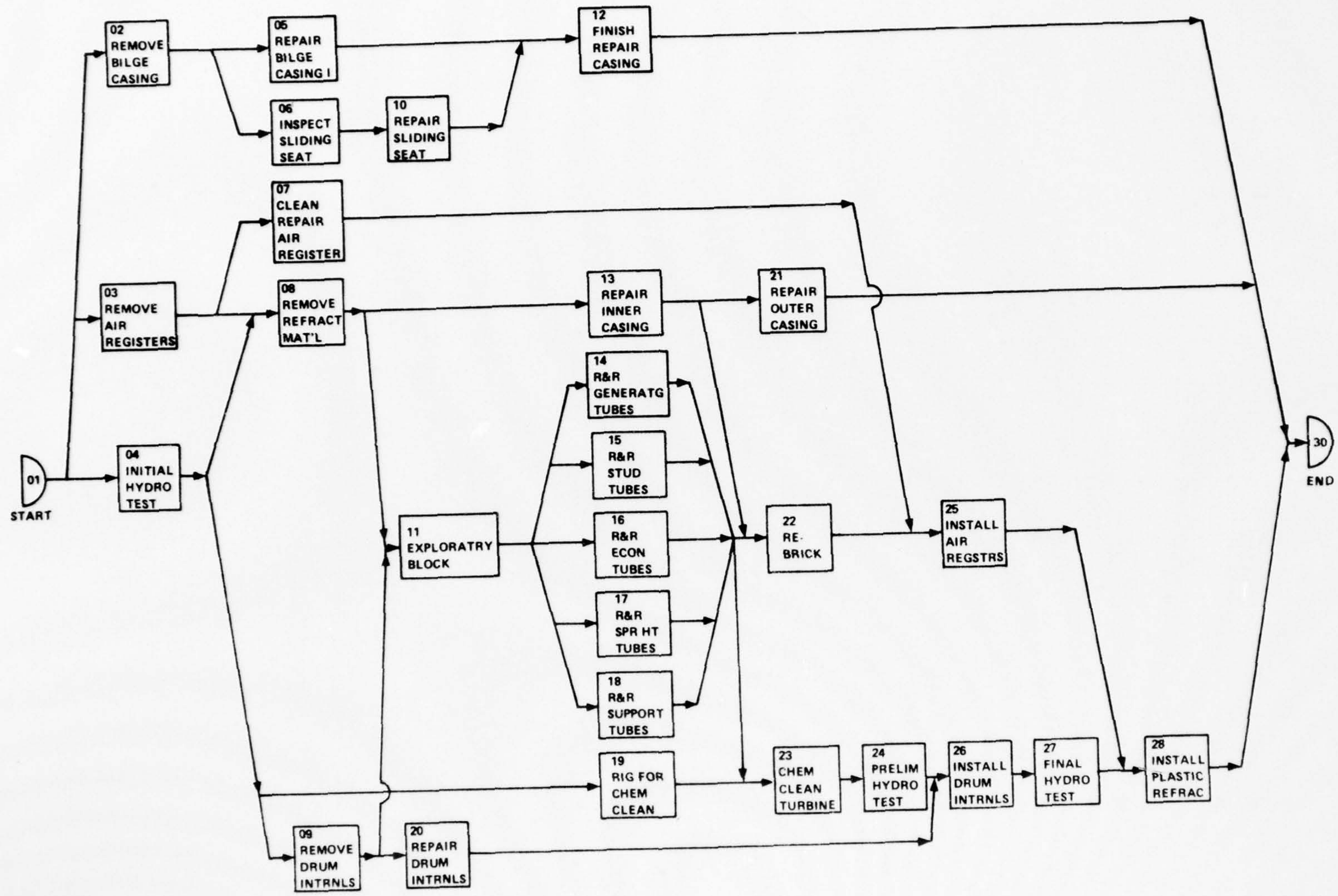
2 Activity "criticality" may be viewed as a direct measure of the activity's sensitivity, i.e., its importance to overall project performance. Criticality is measured in percent between zero and 100; the higher the percent criticality, the more the activity's impact on overall project performance.

3 Estimation methods for activity duration are many and varied. However, only a limited amount of research on the subject has been published. The original PERT System requires three time estimates for each activity: an optimistic (minimum), a most likely (modal), and a pessimistic (maximum) time. A mean or expected value is derived from the three estimates and used for the network analysis. Most other deterministic methods require a single value; i.e., a "best." "normal," "most likely," or "average" time to perform the activity in question.



Project Activity Network
Ship Boiler Repair Project
Figure 1

TABLE I

ACTIVITY DURATION TIMES, WORKDAYS

		Probabilistic			
Activity	Deterministic	Optimistic	Most Likely	Pessimistic	Expected
02	11	3	7	20	11
03	2	0.5	1	3	2
04	3	1	2	5	3
05	26	10	20	45	26
06	5	2	5	8	5
07	30	10	30	50	30
08	7	4	5	10	7
09	2	0.5	1	3	2
10	21	8	24	32	21
11	11	7	8	18	11
12	23	10.5	18	39	23
13	37	20	37	54	37
14	20	10	20	30	20
15	20	6	18	36	20
16	21	13	18	31	21
17	21	8	16	36	21
18	21	6	12	42	21
19	10	5	6	17	10
20	12	5	12	18	12
21	17	5	17	29	17
22	7	5	6	10	7
23	3	1	2	5	3
24	6	1	3	14	6
25	6	1	7	10	6
26	6	2	7	8	6
27	2	1	2	3	2
28	1	0.5	1	2	1
29	--	6	10	15	10
31	--	1	3	8	4

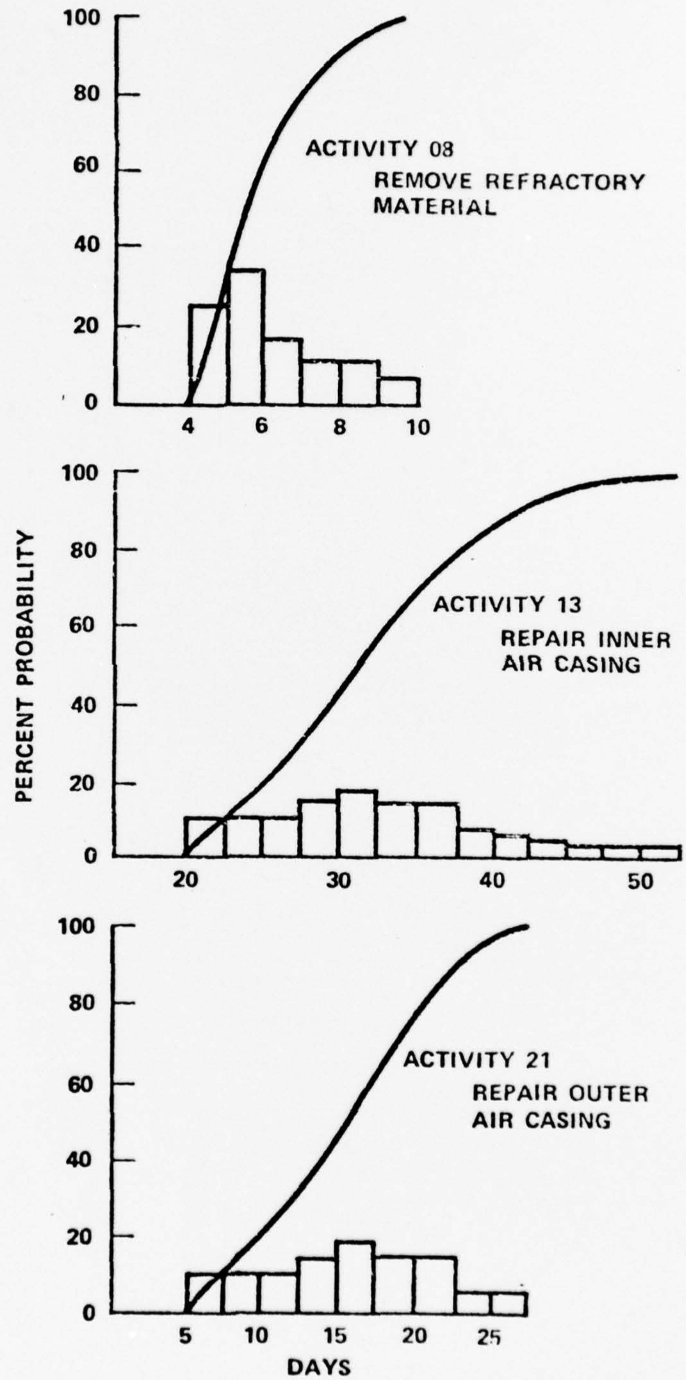


Figure 2. Ship Boiler Repair Activity Time Histograms and Cumulative Frequency Distributions.

Repair Inner Casing, and Activity 21 - Repair Outer Casing of the Ship Boiler Repair Network.

As is apparent from Figure 2, the variability of activity time duration can be significant and yet differ considerably from activity to activity. In the case of Activity 08, the variability of activity time performance is not only due to worker behavior and environmental influences, but also to the uncertain condition of the boiler refractory material at the time the boiler repair project activity performance estimates were initially prepared. Actual condition of the material is usually not known until the task of refractory material removal is actually under way.

For the purposes of this investigation, the ship boiler repair network is analyzed first deterministically, then probabilistically. In the latter case a Monte Carlo computer simulation technique is used which executes the project network 1000 times, basing each project realization on activity times which are independently sampled from the input distributions of possible times for each individual activity. Activity duration are input in the form of a modified triangular distribution,[4] fit to the three (optimistic, most likely, and pessimistic) estimates listed in Table I. A series of separate investigations are undertaken, each designed to demonstrate a different shortcoming of deterministic network analysis. In all cases, it is assumed that the activity duration estimates are at "best," unbiased values obtained from historical or expert subjective judgement sources. A listing of the related computer simulation runs is given in Table II.

<u>ANALYSIS RESULTS - Run A (Deterministic)</u>

An initial, deterministic analysis (Run A) of the boiler repair project

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[4] The modified triangular distribution is based on the assumption that the optimistic and pessimistic estimates are 5th and 95th percentile values, respectively.

TABLE II

LISTING OF COMPUTER SIMULATION RUNS

Run	Description
A.	Deterministic with resource requirements.
B.	Probabilistic with earliest starts and resource requirements.
C.	Probabilistic with latest allowable starts.
D.	Probabilistic with earliest starts and probabilistic branch.
E.	Probabilistic with earliest starts and increased activity duration variability.
F.	Probabilistic with earliest starts and deterministic resource allocation.

network provides the basis for demonstrating the specific bias shortcomings of conventional critical path techniques. The deterministic analysis is based on the single-value activity durations listed in Table I.

Run A results shown in Figure 3 indicate that the project would be completed on Day 64, which matches the total of activity durations along the longest time path through the network, including activities 04, 08, 13, and 21, with durations of 3, 7, 37, and 17 workdays, respectively. Such a single value completion time is characteristic of the conventional deterministic critical path technique.

Run B (Probabilistic - Merger Bias)

The probabilistic analysis, Run B, provides a demonstration of the "merger bias"[5] factor which is a major contributor to the optimistic bias of deterministic network analysis. The comparison with Run A results is based on earliest start times for the individual activities of the network.

Run B results shown in Figure 4 indicate that the shortest possible project completion time is Day 57 and the longest, Day 105. Further, the probabilistic results indicate that the Day 64 deterministic completion time (Run A) has only a 6 percent probability of being attained. The results also show that the probabilistic average (expected) comple-

---

[5] The term "merger bias" (merge point bias, nodal bias, etc.), refers to the error that is introduced by network analysis techniques in calculating the times by which all activities merging at a node will be completed. Conventional techniques assume that this will be the expected completion time of the latest activity. This time will be in error when it differs from the extreme value calculation of the latest expected completion time of all activities merging at the node.

```
NAVAL SHIP BOILER REPAIR   DETERMINISTIC RUN  (RESOURCES)    30JUL75                                                   PAGE    1
TIME SUMMARY GRAPH    PROJECT OVERALL TIME

TIMES OF MILESTONE  30            END

LONGEST TIME  :        64 WORKDAY
EXPECTED TIME :        64 WORKDAY
SHORTEST TIME :        64 WORKDAY

          INTERVAL                      X = PERCENT PROBABILITY (ROUNDED)               C = CUMULATIVE PERCENT PROBABILITY

                                                  1         2         3         4         5         6         7         8         9         1
  WORKDAY        WORKDAY         1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
         63 OR LESS
 OVER    63 THRU        64       XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXC
       MORE THAN        64
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Figure 3

Time Summary Graph

Deterministic Run (Run A)

NAVAL SHIP BOILER REPAIR PROB. RUN EARLIEST STARTS (RESOURCES) 30JUL75 PAGE 1

TIME SUMMARY GRAPH PROJECT OVERALL TIME

TIMES OF MILESTONE 30 END

LONGEST TIME : 105 WORKDAY
EXPECTED TIME : 76 WORKDAY
SHORTEST TIME : 57 WORKDAY

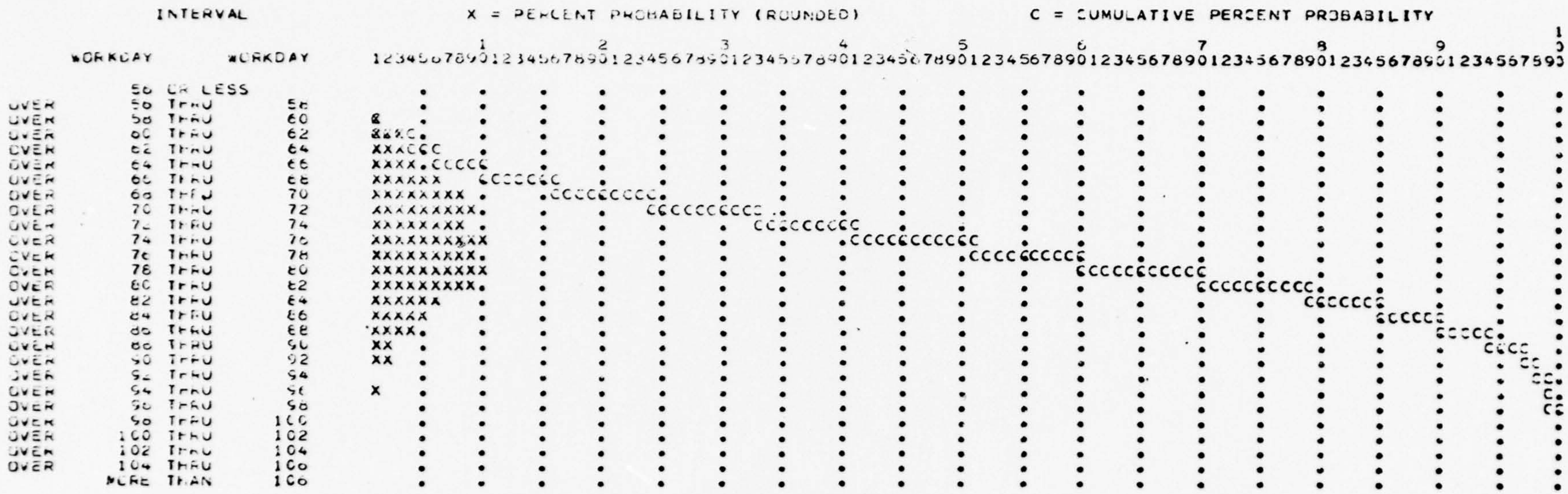


Figure 4

Time Summary Graph

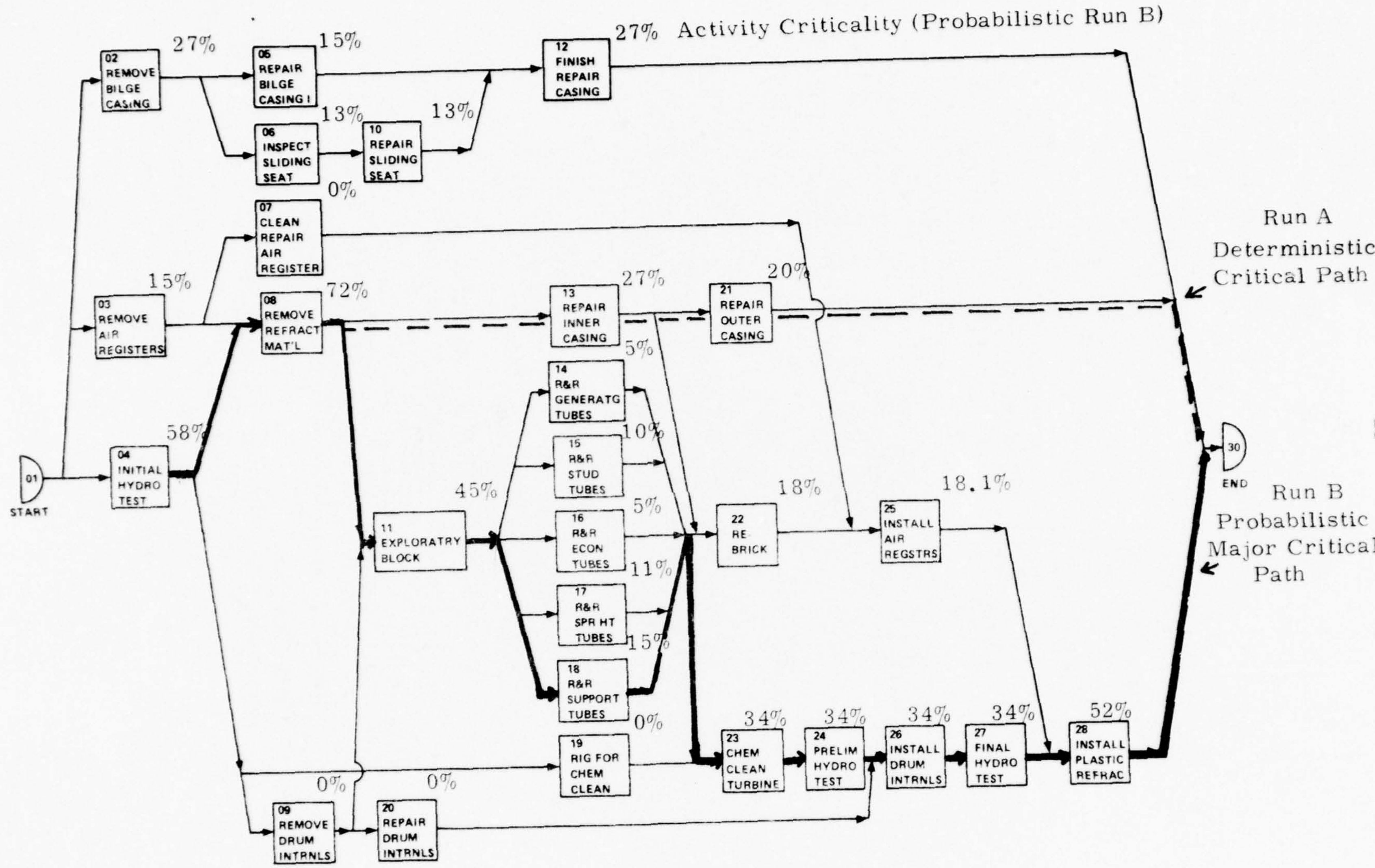
Probabilistic Run, Earliest Starts (Run B)

tion date to be Workday 76, representing a 12 day or 18.75 percent increase in project time when compared with the deterministic completion time of Run A.

Another significant difference between the deterministic and probabilistic results is in the designation of the critical path. The deterministic analysis of Run A identifies a critical path consisting of Activities 04, 08, 13 and 21, as shown by the dashed line in Figure 5. On the other hand, the Run B probabilistic analysis does not identify a single critical path, but instead, different levels of criticality for the several paths as depicted in Figure 5. It should be noted that the deterministic critical path through Activities 04, 08, 13 and 21 is not the most "critical" of the several paths in the probabilistic run. The probabilistic most "critical" path runs through Activities 04, 08, 11, 18, 23, 24, 26, 27, and 28. Activities 02 and 12 on a path with lesser criticality have higher criticality values than Activity 21 on the deterministic critical path of Run A. Thus, it is apparent that the deterministic results of Run A are not only optimistic, but can as well be misleading with regard to activity criticality. Further, it should be noted that individual activities on the same path may have different levels of criticality.

The optimistic bias of the deterministic analysis results from the multi-path criticality revealed in the probabilistic run. This is because of the "merger bias" which produces slippage at all network nodes where there is a merger of two or more activities with criticality.

The significance of "merger bias" is apparent by reference to Table I. The deterministic critical path of Run A has a total path length of 64 workdays. On the other hand, the major critical path of Run B has individual, expected activity durations, totaling 60 workdays, or 4 days <u>less</u> than the deterministic critical path. Yet, the impact of "merger bias" at the nodes along the several paths with criticality causes an increase in overall completion time of the project to 76 workdays.



Critical Path and Activity Criticality
Ship Boiler Repair Project

Figure 5

Run C (Late Start Bias)

Run C demonstrates another important shortcoming of conventional deterministic techniques - "late start" bias, which becomes a significant factor when activities with criticality are started on dates later than their earliest start dates, as in the cases where "total slack" or "total float" are utilized.

The results for Run C given in Figure 6 indicate an expected (average) completion date of Day 80 according to the probabilistic analysis based on activities starting on the deterministic "latest allowable" start date.[6] This is to be compared with the Run A deterministic Day 64 and Day 76 completion for the probabilistic Run B with earliest starts. In the Run C case, the Run A deterministic completion date has less than a one percent likelihood of being attained. As before, the merger bias is the factor of major significance - this time contributing to a 25 percent penalty in project completion time. The additional bias penalty resulting from the use of the "latest allowable" start date is characteristic of most projects with uncertainty and is due to the individual activities acquiring additional criticality as their start dates are slipped from the earliest start date. As was discussed earlier, the closer the criticality levels of different activities merging at a node, the higher the merger bias at that node.

Run D (Probabilistic Branch)

Another source of optimistic bias in deterministic network analysis can reside in the structure of the project plan itself. With all critical path methods, developing the project activity network consists of deter-

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6 "Latest allowable" start date is defined in deterministic methodology as the latest date an activity can start without directly causing any increase in total time to complete the project.

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NAVAL SHIP BOILER REPAIR PROBABILISTIC RUN WITH LATEST ALLOWABLE STARTS 29JUL75                                  PAGE    1
TIME SUMMARY GRAPH     PROJECT OVERALL TIME

   TIMES OF MILESTONE   30            END

   LONGEST TIME   :     104 WORKDAY
   EXPECTED TIME  :      80 WORKDAY
   SHORTEST TIME  :      63 WORKDAY

           INTERVAL                    X = PERCENT PROBABILITY (ROUNDED)              C = CUMULATIVE PERCENT PROBABILITY
                                                                                                                 1
                                                1         2         3         4         5         6         7         8         9         0
      WORKDAY         WORKDAY          1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890

              62 OR LESS                   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         62 THRU      64              .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         64 THRU      66          C   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         66 THRU      68          CCCC.    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         68 THRU      70          XXXCCCC  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         70 THRU      72          XXXXX CCCCCCC .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         72 THRU      74          XXXXXXX  .  CCCCCCCC    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         74 THRU      76          XXXXXXXXXX    .    CCCCCCCCCCC    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         76 THRU      78          XXXXXXXXXX    .    .    .    CCCCCCCCCCC    .    .    .    .    .    .    .    .    .    .    .    .
 OVER         78 THRU      80          XXXXXXXXXX    .    .    .    .    .    CCCCCCCCCCC    .    .    .    .    .    .    .    .    .    .
 OVER         80 THRU      82          XXXXXXXXXXX   .    .    .    .    .    .    .    CCCCCCCCCCCCC  .    .    .    .    .    .    .    .
 OVER         82 THRU      84          XXXXXXXXXX    .    .    .    .    .    .    .    .    .    .  CCCCCCCCCCC  .    .    .    .    .    .
 OVER         84 THRU      86          XXXXXXXXX.    .    .    .    .    .    .    .    .    .    .    .  CCCCCCCCCC   .    .    .    .
 OVER         86 THRU      88          XXXXXXXX .    .    .    .    .    .    .    .    .    .    .    .    .    .    .CCCCCCCCC.    .    .
 OVER         88 THRU      90          XXXX.    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   CCCCCC.    .
 OVER         90 THRU      92          XXX .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   CCC   .
 OVER         92 THRU      94          XX  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .CCCC.
 OVER         94 THRU      96          X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   C.
 OVER         96 THRU      98          X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  CCC
 OVER         98 THRU     100              .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER        100 THRU     102              .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
 OVER        102 THRU     104              .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
            MORE THAN     104              .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
```


Figure 6

Time Summary Graph

Probabilistic Run, Latest Allowable Starts (Run C)

mining the precedence relationships of the individual project activities which then provides the "road map" for project implementation. However, in conventional deterministic planning, an assumption is made that each activity has a 100 percent probability of occurring and that the sequential arrangement of activities has a 100 percent probability of being executed as initially planned.

Such an assumption does not account for the common planning uncertainties of real life projects. Examples such as those following are numerous: working drawings may be returned to the design agent several times for revisions before being accepted; unanticipated ground waters may be encountered while excavating, requiring the obtaining of pumps; budget approvals may be delayed pending the submittal of additional supporting information; and testing may reveal system "bugs" which require correction, perhaps even system redesign. Such planning uncertainties can have a significant impact on the probability of attaining project goals.

As an illustration, for the boiler repair network of Figure 1, the planner might estimate that based on experience there is a 20 percent probability that the preliminary hydro test (Activity 24) will fail when it is first performed. In such a case it would be necessary to check out the entire assembly, isolate the problem, and then make the necessary repairs before resubjecting the assembly to the hydro test.

The system recheck, repair and retest will require time and resources to perform and as a result can have impact on project completion time. Whereas the deterministic planner has no means of accounting for the uncertainty, the probabilistic planner can allow for such uncertainty by adding two activities -- Activity 29 - Check and Repair and Activity 31 - Rerun Preliminary Hydro Test, succeeding Activity 24 - Preliminary Hydro Test, as shown on Figure 7. In order to account for the uncertainty regarding the test results, he can assign a 20 percent probability value to the network branch leading to Activity 29, which will account for the probability that the hydro test will fail, and an 80

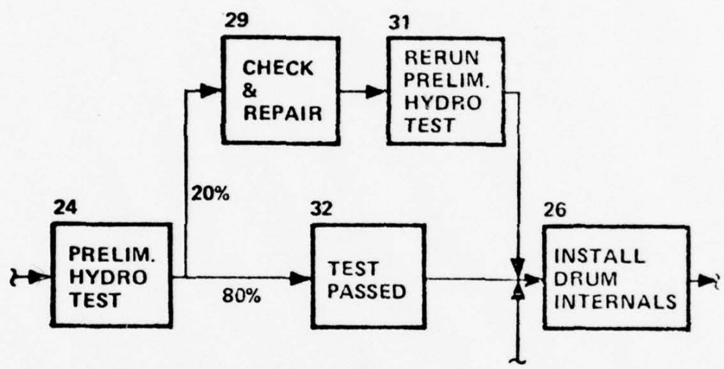

Figure 7. **Probabilistic Branch Boiler Repair Network.**

percent probability value to the original direct path from Activity 24 to Activity 26 (through a new Activity 32 - Test Passed). The durations for Activities 29 and 31 are given in Table I.

During the Run D probabilistic network analysis, the longer activity 29 (test fails) branch was selected in 20 percent of the project realizations with resultant lengthening of the overall project completion time. The analysis results given in Figure 8 indicate a Day 78 expected project completion. It is apparent that the impact of the probabilistic branch on overall project performance is measurable, resulting in a 2 day, or a 2.6 percent delay beyond the Day 76 project completion date for Run B (which did not account for the possibility of unsuccessful hydro testing of the boiler) and as well, a 22 percent increase over the deterministic completion time of Run A.

Run E (Activity Duration Variability)

Another factor affecting the optimistic bias of deterministic network analysis is the degree of variability of activity duration times. As before, the deterministic optimism results from merger bias at the nodes; in this case, the more the variability of activity performance, the greater the merger bias.

Run E has the objective of demonstrating the significance of activity duration variability. For the boiler repair network of Figure 1, the "optimistic" and "pessimistic" duration times for Activity 13 - Repair Inner Casing (see Table 1) are extended 15 days, respectively, to 5 and 69 days, with the "expected" value remaining at 37 days. Such variability is not unusual for cases of repair work on items utilized in the marine environment.

The analysis results given in Figure 9 show that the increase in variability of the single activity extends the project completion date to Day 79 or 3 days later than Run B. Were other critical activities to be similarly affected, the project slippage would increase still further.

NAVAL SHIP BOILER REPAIR PROBABILISTIC BRANCH AND EARLIEST STARTS 29JUL75 PAGE

TIME SUMMARY GRAPH PROJECT OVERALL TIME

TIMES OF MILESTONE 30 END

LONGEST TIME : 109 WORKDAY
EXPECTED TIME : 78 WORKDAY
SHORTEST TIME : 55 WORKDAY

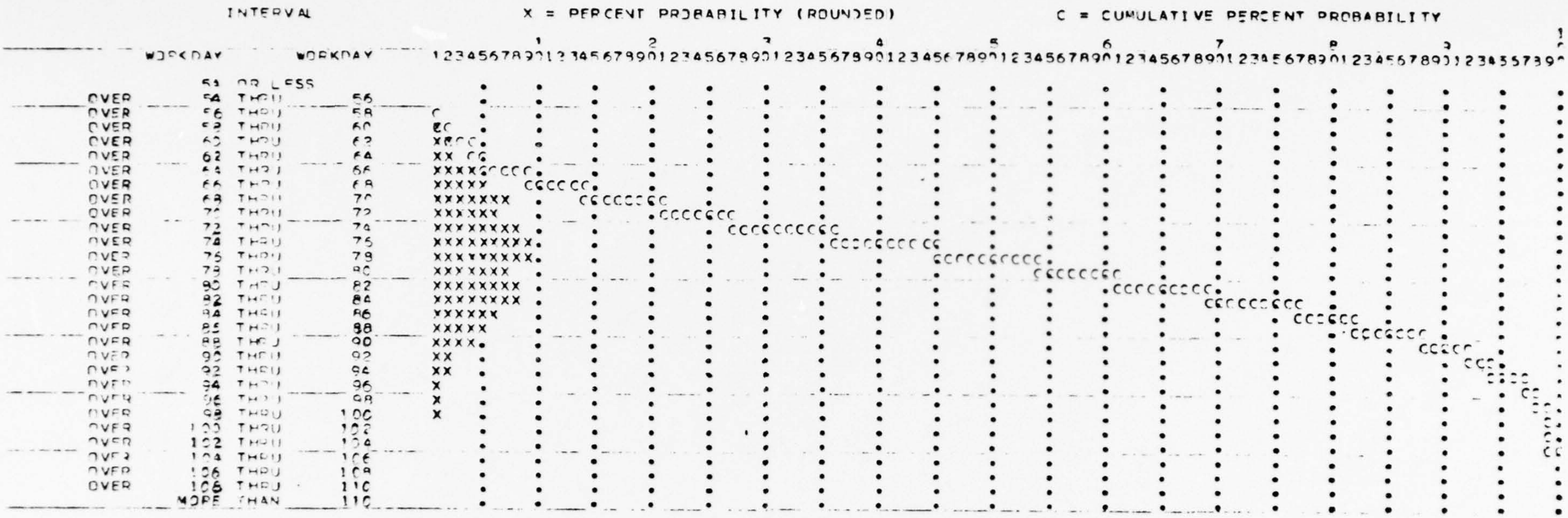

Figure 8

Time Summary Graph

Probabilistic Branch, Earliest Starts (Run D)

NAVAL SHIP BOILER REPAIR PROB. RUN EARLIEST ST. (RESC) ACT. DUR. 30JUL75 PAGE 1

TIME SUMMARY GRAPH PROJECT OVERALL TIME

TIMES OF MILESTONE 30 END

LONGEST TIME : 111 WORKDAY
EXPECTED TIME : 79 WORKDAY
SHORTEST TIME : 54 WORKDAY

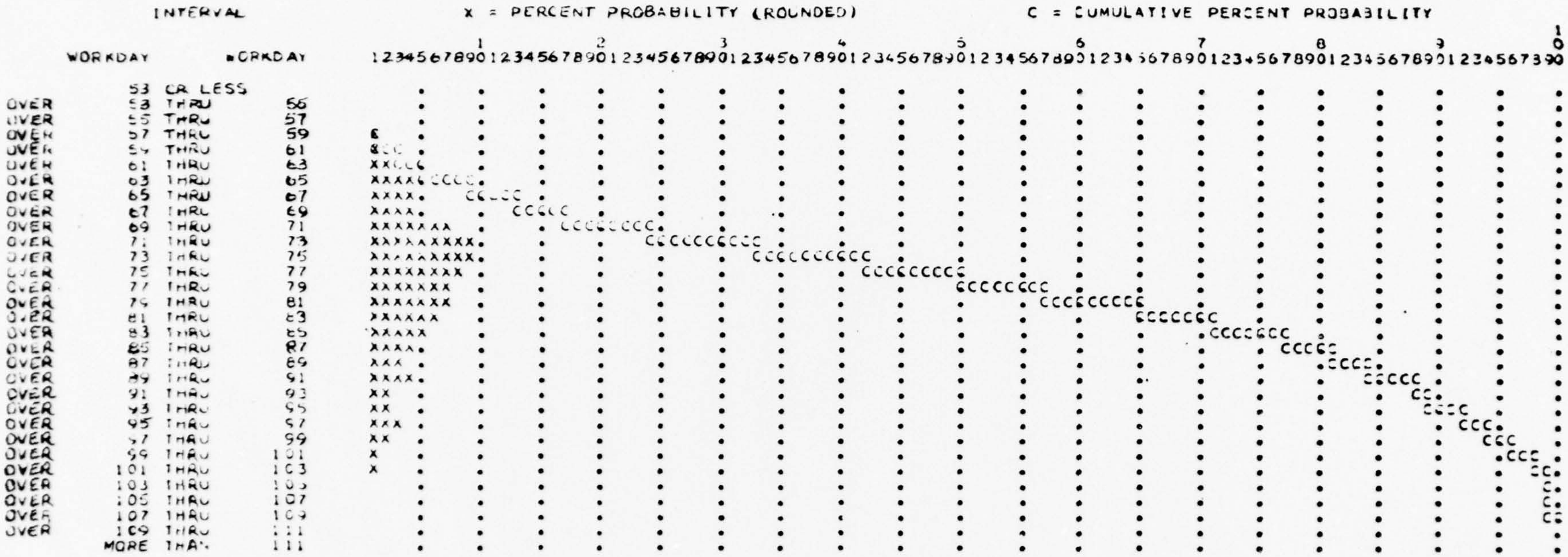

Figure 9

Time Summary Graph

Probabilistic Run, Earliest Starts with Increased Variability in Activity Duration (Run E)

Conversely, were the activity duration variability to be decreased, the merger bias would be reduced.

Run F (Resource Analysis)

Projects always have requirements for resources such as manpower, materials, machines, tools, facilities, and capital. All project performances typically suffer from some scarcity of resources and the net effect is invariably project slippage. Accordingly, analysis of the tradeoffs between schedule and level of available resources is key to effective project management.

Resource analysis capabilities are included in many of the conventional deterministic network techniques. Typically, the planner first develops the schedule. Next, he sums up the requirements for specific resources. Usually, the first summation will show high and low peaks in the demand for resources when viewed over the length of the project. Where the supply of resources is ample, the management task is simple, that is, merely to assure that the resources are at the right place when required. On the typical project, however, most resources are in limited supply especially for the highly specialized skills. Accordingly, the planner will "level" the resources, that is, establish a resources level compatible with the sometimes conflicting objectives of cost, resource utilization and project time performance.

Although resource analysis and allocation with the deterministic technique is straightforward, it can directly contribute to slippage on projects affected by uncertainty. In such cases, resource requirements must be determined in full consideration of the variability of activity start and finish dates. Hence, the probabilistic network planner deals with the "probabilities" of different levels of resources required on any specific project date.

The requirements for General Maintenance Men on the boiler repair project case are shown in Figure 10 for the deterministic Run A. The requirements fluctuate between a 3 to 4 man level and a peak requirement of 9 men (Day 17).

```
NAVAL SHIP BOILER REPAIR   DETERMINISTIC RUN  (RESOURCES)     30JUL75                                        PAGE    24

RESOURCE REQUIREMENTS GRAPH                                   (CONTINUED)                                    SHEET  A   1

RESOURCE CODE :    MAINTMAN            DESCRIPTION :  GEN. MAINT. MEN
NUMBER OF RESOURCE UNITS AVAILABLE :        20.00

         I = PROJECTED MAXIMUM REQUIREMENTS                          E = EXPECTED REQUIREMENTS

                                          WORKDAYS :         1 THRU        100
```

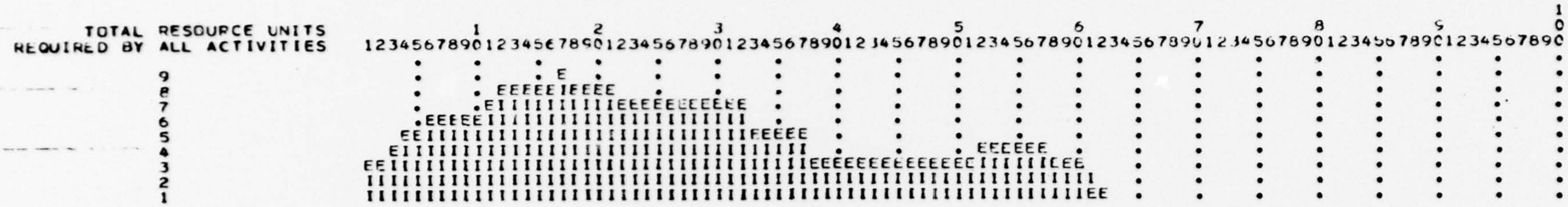

Figure 10

Deterministic Requirements for General Maintenance Men (Run A)

On the other hand, Run B (probabilistic) requirements for General Maintenance Men, shown in Figure 11, indicate that the expected values (E on the graph) do not reach the deterministic peak requirement of 9 men because of activity start slippage due to merger bias. Of more significance, the probabilistic values reveal a considerably different peak requirements pattern during the entire course of the project.

Of importance are the probabilistic peak requirements greater than the expected values. For example, for Day 35, Figure 10 (Run A) shows a deterministic requirement for 5 General Maintenance Men. The equivalent probabilistic requirement (Day 35 - Run B, Figure 11) shows an expected value of 5 General Maintenance Men but with requirement probability of as many as 7 men, depending upon the eventual realization of activity time performance. If the 7 - man requirement is actually realized, but there are only 5 available, the demanding activities will slip, thereby penalizing overall project performance if the demanding activities have some level of criticality.

Run F is designed to demonstrate the optimistic bias penalty due to basing resource allocation on deterministic requirements. In the probabilistic Run F, the allocation of General Maintenance Men follows the pattern indicated in Figure 10 for the deterministic Run A. Run F results shown in Figure 12 indicate a Day 79 project completion date, which represents a 3 day slippage beyond the merger bias impact shown in Figure 4 (Run B). In other words, the combined effect of merger bias and slippage due to deterministic resource allocation results in 23 percent slippage when compared with the deterministic schedule of Run A.

SIMULATION APPROACH

In light of the need for a network analysis technique capable of dealing with project uncertainty, UCLA recently undertook development of a probabilistic network analysis method based on Monte Carlo simulation. Under joint sponsorship of the Office of Naval Research and Naval Sea Systems Command, the project has already produced the operational system,

NAVAL SHIP BOILER REPAIR PROB. RUN EARLIEST STARTS (RESOURCES) 30JUL75 PAGE 31

RESOURCE REQUIREMENTS GRAPH (CONTINUED) SHEET A 1

RESOURCE CODE : MAINTMAN DESCRIPTION : GEN. MAINT. MEN
NUMBER OF RESOURCE UNITS AVAILABLE : 20.00

I = PROJECTED MAXIMUM REQUIREMENTS E = EXPECTED REQUIREMENTS

WORKDAYS : 1 THRU 100

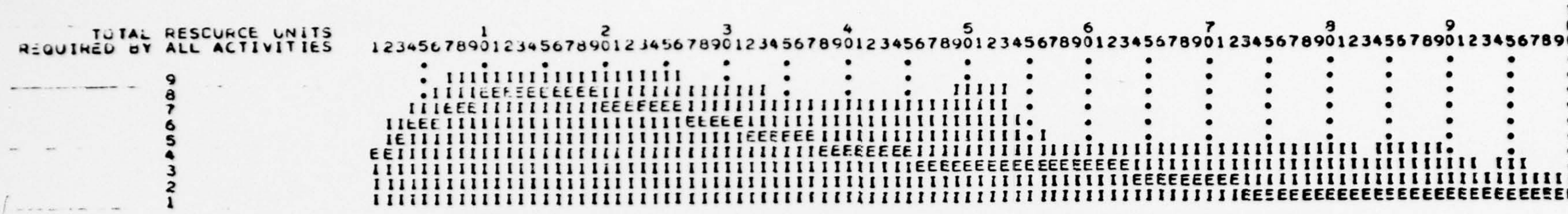

Figure 11

Probabilistic Requirements for General Maintenance Men (Run B)

```
    NAVAL SHIP BOILER REPAIR  PROB. RUN EARLIEST STARTS (VAR. RESOURCES)   1AUG75                                   PAGE    1
 TIME SUMMARY GRAPH    PROJECT OVERALL TIME

   TIMES OF MILESTONE  30           END

   LONGEST TIME  :     108 WORKDAY
   EXPECTED TIME :      79 WORKDAY
   SHORTEST TIME :      64 WORKDAY

           INTERVAL                    X = PERCENT PROBABILITY (ROUNDED)            C = CUMULATIVE PERCENT PROBABILITY
                                                                                                                             1
                                   1         2         3         4         5         6         7         8         9         0
      WORKDAY      WORKDAY    1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890

        63 OR LESS                .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    63 THRU     65        XC  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    65 THRU     67        XCCCCCC  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    67 THRU     69        XXXXXXCCCCCCC .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    69 THRU     71        XXXX.    .  CCCCC  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    71 THRU     73        XXXXXXXXXX    . CCCCCCCCCCCC .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    73 THRU     75        XXXXXXX  .    .    .    .  CCCCCCCC.    .    .    .    .    .    .    .    .    .    .    .    .    .
OVER    75 THRU     77        XXXXXXXXXXXX  .    .    .    .   CCCCCCCCCCCCCC  .    .    .    .    .    .    .    .    .    .    .
OVER    77 THRU     79        XXXX.    .    .    .    .    .    .    .    .CCCCC    .    .    .    .    .    .    .    .    .    .
OVER    79 THRU     81        XXXXXXXXXX    .    .    .    .    .    .    .    CCCCCCCCCCCC   .    .    .    .    .    .    .    .
OVER    81 THRU     83        XXXXXXXXX.    .    .    .    .    .    .    .    .    .    .CCCCCCCCCC    .    .    .    .    .    .
OVER    83 THRU     85        XXXXXXX  .    .    .    .    .    .    .    .    .    .    .    .    CCCCCCCC  .    .    .    .    .
OVER    85 THRU     87        XXXXX    .    .    .    .    .    .    .    .    .    .    .    .    .    .CCCCCC   .    .    .    .
OVER    87 THRU     89        XXXXXXXXXXX   .    .    .    .    .    .    .    .    .    .    .    .    .    .CCCCCCCCCCCC  .    .
OVER    89 THRU     91        X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . CC .    .
OVER    91 THRU     93        XX  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   CCC   .
OVER    93 THRU     95        X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .CC  .
OVER    95 THRU     97        XX  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . CCC.
OVER    97 THRU     99        X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  CC.
OVER    99 THRU    101            .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   C.
OVER   101 THRU    103            .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   C.
OVER   103 THRU    105            .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   C.
OVER   105 THRU    107            .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   C.
OVER   107 THRU    109        X   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   CC
      MORE THAN    109            .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
```

Figure 12

Time Summary Graph

Probabilistic Run, Earliest Starts with Deterministic Resource Allocation (Run F)

TABLE III

SUMMARY OF RESULTS

Run Description	Project Completion Time			Deterministic Optimistic Bias (Percent)	Prob. of Proj. Comp. by Deterministic Comp. Date (Percent)
	Shortest	Expected	Longest		
A. Deterministic	--	64	---	--	100
Probabilistic					
B. Merger Bias	57	76	105	19	6
C. Late Start Bias	63	80	104	25	less than 1
D. Probabilistic Branch	58	78	100	22	5
E. Activity Duration Variability	54	79	111	23	7
F. Resource Analysis	64	79	108	23	1

PROMAP. The probabilistic technique has been receiving increasing interest in government and industry and has already been applied to projects totaling over $10 billion in value, including widely diverse applications such as:

- Ship acquisition, overhaul planning, overhaul modernization and repair
- Off-shore oil platform design, fabrication and installation
- Hospital planning and construction
- Land development planning and construction
- Rail line relocation
- Air traffic control system design and implementation
- Institution and industrial plant relocation
- Nuclear fuel management
- Naval shore facility design and construction
- Public works design and construction

The probabilistic technique is used in a manner similar to the conventional methods of deterministic network analysis, except that it allows input of:

1) variable activity durations, costs and resource requirements instead of the fixed, single input values of the deterministic methods
2) variable network paths instead of the fixed activity relationships of the deterministic methods

Such variabilities can have a profound impact on almost all decisions faced by project management related to planning, scheduling, resource allocation, costs, cash flow, and budget control.

Although similar in concept to conventional techniques, there are some fundamental differences in management philosophy employed during the project management process with the probabilistic technique. Such differences generally manifested throughout the project -- from planning through project control and completion.

Planning

For example, there is a difference in rationale applied by the planner to the networking task. As was discussed earlier, the probabilistic planner can account for plan uncertainties through the use of probabilistic network branches involving activities which have less than 100 percent probability of occurring.

The difference in planning rationale applies as well to the overall planning effort. Because of the wide recognition of the problems of project control inherent to conventional techniques, deterministic planners tend to construct activity networks in which the longest path is "overcritical," that is, significantly longer than any other path. This is done to reduce the likelihood of near-critical paths becoming critical during the course of the project, thus complicating the project control task. Yet, in most cases, project cost increases with project duration and longer than necessary critical paths can result in high cost penalties.

On the other hand, with a probabilistic network analysis capability and its attendant ability to quantify the effects of project task variability for control purposes, the probabilistic planner can construct a minimum time network without apprehension regarding the relative criticality of alternative paths. Reducing project time in most cases decreases project cost.

Network Analysis

With the probabilistic technique the project "model" (activity network plus data) undergoes analysis by being "run" in the computer as many as several hundred times, each run representing a complete project realization from start to finish. During each project realization, activity durations, costs and resource requirements as appropriate, are randomly sampled from the input data describing ranges of values for the individual activities.

The results consist of schedules, costs, resource requirements, and

other pertinent project statistics including ranges of values between minimum and maximum, as well as the probability of any value between the two extremes. Such data are included on the Time Summary Graphs and Resource Reports shown in this paper - two of several types of output reports in PROMAP.

Scheduling

Project managers using conventional critical path techniques are not universally aware that the project completion time and schedules produced by their deterministic methods have only about a 50 percent probability of being attained. For important events such as the completion of a technical development, delivery of major equipment, or completion of ship construction, the project manager would probably find such a high level of risk to be unacceptable.

With the probabilistic PROMAP the project manager can develop a project schedule conforming to any desired level of project risk. For example, in the case of completing a technical development, the project manager might develop a project plan which would produce a scheduled completion date with a 75 percent probability of being attained (or a 25 percent risk that the scheduled completion date would be exceeded). For the completion of a new weapon system training school, the desirability of a school opening date no later than the start of the regular school year might cause selection of a schedule which would provide a 95 percent probability that the school would be ready in time. For a weapon system acquisition, the project manager could select a schedule for delivery reflecting a 90 percent probability of attainment (or a 10 percent risk of being late).

Costing

The use of the probabilistic technique facilitates project cost analysis and control. The project network is in effect the project "model" for scheduling and cost estimating. By including for each activity variable cost elements such as labor, material, indirect costs and escalation

factors, probabilistic network analysis provides a powerful means of improving cost estimating and cost control of projects. In particular, accounting for the impact of uncertainty on project time performance, the probabilistic technique provides a more realistic base for cost computations.

Risk-taking

Capacity for risk-taking differs among individuals and under different decision circumstances. Hence, project managers on different types of projects have different acceptable levels of risk, dependent perhaps on diverse considerations such as total cost, size of investment, safety, interaction with other projects, national security, lost revenue, weather (completing before winter, etc.), availability of budget funds, etc. The ability of the project manager to select a project schedule, budget, and resource allocation to fit his acceptable level of risk is one of the unique features of the probabilistic network analysis technique.

CONCLUSIONS

It is fundamental to most major projects that uncertainty and variability have measurable impact on the project plan and on project time and cost performance. The shortcomings of conventional network analysis techniques when applied to such projects have been recognized almost since the introduction of PERT and CPM. Because they are deterministic and therefore cannot account for project uncertainty and variability, conventional methods tend to produce optimistic schedules and budgets when applied to projects where such factors are significant - the greater project uncertainty, the larger the optimistic bias of deterministic network techniques.

In the network analysis of the boiler repair project described herein, the specific factors contributing to the optimistic bias of deterministic techniques are demonstrated to be of significance (see Table III) by comparison with probabilistic network analysis results. Projects which contain many or all such factors experience an additive impact; In the case considered, for example, combining bias factors produces a net optimistic bias of over 35 percent.

Investigators have commonly used Monte Carlo computer simulation to provide a realistic basis for comparison in demonstrating the shortcomings of the deterministic methods. Probabilistic network analysis based on computer simulation produces realistic project goals by overcoming the optimistic bias shortcomings of conventional deterministic network analysis techniques. The recently developed probabilistic network analysis technique, PROMAP, accounts for project uncertainty and variability, making possible improved project planning, scheduling, budgeting and control through implementation of project risk analysis.

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3. Van Slyke, R. M., "Monte Carlo Methods and the PERT Problem," <u>Operations Research</u>. <u>11</u>(5): 839-860, 1963.

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